Development of RF Energy Harvesters for Low Power Wireless Sensor Networks

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論 文 名：Development of RF Energy Harvesters for Low Power Wireless Sensor Networks
（低消費電力無線センサネットワークのための RF エネルギーハーベスタの開発）

区　　分：甲

論 文 内 容 の 要 旨

Energy is a significant constraint for wireless communication devices that are generally dependent on limited capacity batteries. In recent years, energy harvesting has been investigated as an alternative energy source for low-power communication nodes. Energy harvesting circuits gather ambient energy from sunlight, vibration, air flow, thermal gradient or other types of harvestable energy sources. Similarly, energy harvesting from radio frequency (RF) signals is also considered as an alternative solution when utilized jointly with advanced semiconductor technology. In RF energy harvesting (RFEH) systems, a wireless node equipped with energy harvesting circuit captures radio signal from ambient by its antenna, then converts radio signal energy into direct current (DC) energy. The amount of harvested RF energy may not be sufficient to directly power-up the node. Therefore, the harvested energy from received DC signals is commonly used to recharge the battery of wireless node, which is utilized to receive, process, and transmit information when required. In order to ensure sustainable communications, it is necessary to harvest the sufficient amount of energy and extend the lifetime of battery as required by the used application. In this study, we introduce several investigations for different ways to improve the amount of harvested RF energy. These approaches can be stated as special designs of circuit, antenna, and signal types for RFEH systems as well as the use of multiple antennas, multiple frequency bands, and power management systems.

In this study, we introduce an investigation of the recent advancement in the RF energy harvesting techniques. Besides, we developed new rectifier circuit topologies for improving the overall conversion efficiency, minimize the circuit footprint, maximize the circuit performance, deploy with a real application like WSN, and simple circuit design technique so facilitate procedures of the circuit implementation. These features offer a great advantage to the proposed design.

The different rectifier circuit configurations either based on the CMOS or the Schottky diode are discussed in chapter 2. Both the analysis and characterization of each circuit are conducted and a full comparison is made between them to get out the most efficient circuit.

After analyzing the performance of the different rectifier architecture, an energy harvesting circuit based on the Schottky diode elements operating at 2.45 GHz is designed, evaluated, and characterized. In chapter 3, a single band rectifier is illustrated. The receiving antenna is a coplanar waveguide (CPW) slot monopole antenna with harmonic suppression property and a peak measured gain of 3 dBi. Also, improved antenna radiation characteristics, e.g radiation pattern and gain covering the desired operating band (ISM 2.45 GHz), is observed. The peak efficiency (40% at -5 dBm) achieved is lower than expected. To improve the efficiency, a high compactness and simple integration between antenna and rectifier are achieved by using a smooth CPW-MS transition. This design shows improved conversion efficiency measurement results which typically agree with the simulation results. The measured peak conversion efficiency is 72% at RF power level of -7 dBm and a load resistance of 2 kΩ.

The second design presents the implementation of a compact, reliable, effective, and flexible energy harvesting (EH) rectenna design. It integrates a simple rectifier circuit with a circularly polarized one-sided slot dipole antenna around 2.45 GHz ISM frequency band for wireless charging operation at low incident power densities, from 1 to 95 uW/cm^2. In order to maximize the system efficiency, the matching circuit introduced between the rectifier and antenna is optimized for a minimum number of discrete components and it is constructed using multiple of L-slot defects in the ground plane. For a given input power of -6 dBm intercepted by the circularly polarized antenna with 3 dBi gain, the peak RF-DC conversion efficiency is 59.5%.

Broadband rectifiers are essential to extend the efficient operating response over a wide frequency band. A compact and 1.5 Octave bandwidth rectifier is demonstrated in chapter 4. The proposed circuit can collect signals efficiently over broad bandwidth spanning from 0.87 to 2.7 GHz, which includes UHF ISM 900 MHz, GSM 900 and 1800 MHz, wireless communication, PCS, and ISM 2.4 GHz. The rectifier has a measured conversion efficiency exceeding 30% from 870 MHz to 2.5 GHz at 0 dBm input power and a load terminal of 2kOmega and a DC output voltage equal to 1 V. The circuit sensitivity may reach up to -20 dBm with DC output voltage 8 mV and 8% conversion efficiency. The maximum measured efficiency is 63% from 1.1 GHz to 1.35 GHz.

All modern electronic devices should be supplied with a balanced DC voltage. Therefore, the majority of power supply circuit should be followed by a conditioning circuit that convert from an unbalanced DC voltage to a balanced form. This will add a circuit complexity and increased large size. To eliminate such issue, we developed a differential energy harvesting circuit that could provide the power directly to the electronic devices without the need for any conditioning circuit. The design of differential rectifier is introduced in chapter 5. The proposed configuration aims to improve efficiency over extended bandwidth of operation, and further size reduction for low profile RF rectifier circuit. The proposed topology provides a measured RF-DC efficiency more than 30% over a relatively wide bandwidth (550MHz) from 0.95GHz to 1.5GHz. Commercial balanced-unbalanced (BALUN) component is used for port transformation. Experimental results show that the system can work with different carrier frequencies and the proposed converter can provide a regulated output voltage of ±1V over the proposed frequency band at RF input power Pin=5dBm. The peak conversion efficiency of the whole system is 57.5% at 1.1GHz.

A rectifier circuit based on 180nm CMOS technology is explained in chapter 6. The proposed circuit is designed and tested at operating frequency 2.45 GHz. The functionality of the rectifier design, which operates from 1.8 to 4.2 GHz, is studied through simulation in Agilent, ADS and implementation using Cadence, Virtuoso. The simulation and measurement results reveal that the harvester could provide a 2.1 VDC with 5 dBm input power and the efficiency is maintained above 30% over the frequency band of interest. The peak efficiency obtained from the rectifier architecture is 51% at excitation frequency 2.6 GHz, input power 5 dBm and a terminal load of 3.5 kΩ.

A real application for the different proposed energy harvesting circuits is demonstrated in chapter 7. The deployment of an energy harvesting circuit is achieved with a Bluetooth low energy unit (BLE) which is attached with multitude of environmental sensors to measure various physical phenomenon. We introduce an experimental demonstration for wireless energy harvesting application. Bluetooth low energy (BLE) unit connected to an array of sensors is used in conjunction with the proposed RF wireless rectenna. Two applications are proposed; the first application is feeding an array of sensors connected to the BLE unit. In this scenario, the rectenna is composed of a circularly polarized spiral antenna and a microstrip RF voltage doubler rectifier.

A future plan is considered in chapter 8. The theme of the forthcoming research work will further improve the harvesting circuits to maximize the efficiency for the micro-power input levels.